Day-night asymmetries of low-energy electrons in Saturn's inner magnetosphere

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[1]   We examine the day-night asymmetry of near-equatorial low energy (12–100 eV) electron fluxes measured by Cassini from July 1, 2004 through April 1, 2010. This energy range is also known to be associated with interchange injections. The electrons are separated into field-aligned (0° to 20° and 160° to 180°) pitch angles and trapped (70° to 110°) pitch angles. There is a stronger day-night asymmetry for the trapped than the field-aligned electrons, but both show enhanced energy fluxes on the nightside relative to the dayside. The dayside electron fluxes decrease sharply at an L-shell of 8, while the nightside electrons exhibit a slow decline in to L = 5. Our finding, along with previous research of high energy electrons, shows that this asymmetry is energy independent. This suggests that interchange injections are stronger, and therefore penetrate deeper into the magnetosphere, on the nightside. **Citation:** DeJong, A. D., J. L. Burch, J. Goldstein, A. J. Coates, and F. Crary (2011), Day-night asymmetries of low-energy electrons in Saturn's inner magnetosphere, *Geophys. Res. Lett.*, *38*, L08106, doi:10.1029/2011GL047308.

1.   Introduction

[2]   Using Cassini Plasma Spectrometer (CAPS) data *Young et al.* [2004], *Burch et al.* [2005] and *Hill et al.* [2005] found evidence of a centrifugal interchange instability that causes magnetic flux tubes containing low density, high temperature plasma to replace dense, cold plasma in Saturn's inner magnetosphere. When electrons and ions of an interchange injection are observed together, they disperse in opposite directions in the corotating frame, due to gradient-curvature drifts. The azimuthal separation between these dispersions indicates the age of the interchange injection [*Hill et al.*, 2005]. Young, or local, injections exhibit less dispersion and have a decrease in electron energy flux at lower energies (<100 eV) [*Burch et al.*, 2005]. Older injections tend to have more dispersion in the high energy range (>1000) and no longer possess a flux decrease at lower energies. *Chen and Hill* [2008] performed a statistical analysis on 429 separate injections/dispersions and found a local-time asymmetry with injections clustered in the pre-noon quadrant. These plasma injections also appear to have a radial dependence, because they are only found between 5 and 10 R_S [*Burch et al.*, 2005; *Hill et al.*, 2005; *Chen and Hill*, 2008]. *Müller et al.* [2010] analyzed 52 injections, using the Magneto-

spheric Imaging Instrument (MIMI) on Cassini. They traced the injections back to their points of origin and found that the injections occur with a higher frequency in the night and morning sectors.

[3]   *Carbary et al.* [2009] and *Paranicas et al.* [2010] used Low Energy Magnetospheric Measurement System (LEMMS) MIMI data to perform a statistical study of the electrons fluxes in the inner magnetosphere of Saturn. They found larger electron energy fluxes on the nightside relative to the dayside. Also using MIMI measurements, *Krimigis et al.* [2007] identified a local time asymmetry in the ring current and pressure. Thus, numerous studies have shown day-night asymmetries in the Saturnian magnetosphere.

[4]   *DeJong et al.* [2010] showed that increases in the energy flux for 12–100 eV electrons are associated with interchange injections. When averaging 3 years of equatorial data, they identified a peak in energy flux for the 12–100 eV electrons at approximately 8 R_S. They then separated the electrons by pitch angle into trapped and field-aligned populations. While both pitch angle populations exhibited an increase in energy flux associated with injections, the field-aligned electrons showed larger increases relative to the trapped electrons. Therefore, the authors concluded that the field-aligned electrons in the 12–100 eV are more closely linked to the interchange processes than the trapped electrons. They believe that the field-aligned electrons are driven into the magnetosphere from the ionosphere by the field-aligned currents that are associated with interchange injections. *DeJong et al.* [2010, Figure 9a] indicated that there may be a nightside-dayside asymmetry in the 12–100 eV electrons with the nightside electrons penetrating deeper into the magnetosphere. In this investigation, we expand on the findings of *DeJong et al.* [2010] and others by investigating possible dayside and nightside asymmetries in electron energy fluxes measured by CAPS ELS (Electron Spectrometer) in the Saturnian magnetosphere.

2.   Data Selection and Analysis

[5]   While the CAPS ELS instrument on Cassini can measure fluxes of electrons ranging from 0.5 eV to 28,000 eV, only the 12–100 eV electrons are investigated. The lower limit of 12 eV is imposed because 12.6 eV is the ionization energy of water in the gaseous state [*Johnson*, 1990] and because electrons below this range are most likely photoelectrons emitted by the Cassini spacecraft. The upper limit of 100 eV is employed since it is the approximate boundary between the energy ranges of the bimodal electrons identified by *Sittler et al.* [1983] and *Young et al.* [2005] in Saturn's magnetosphere.

[6]   The CAPS ELS data in this study were taken from July 1, 2004 to April 1, 2010 when Cassini was located

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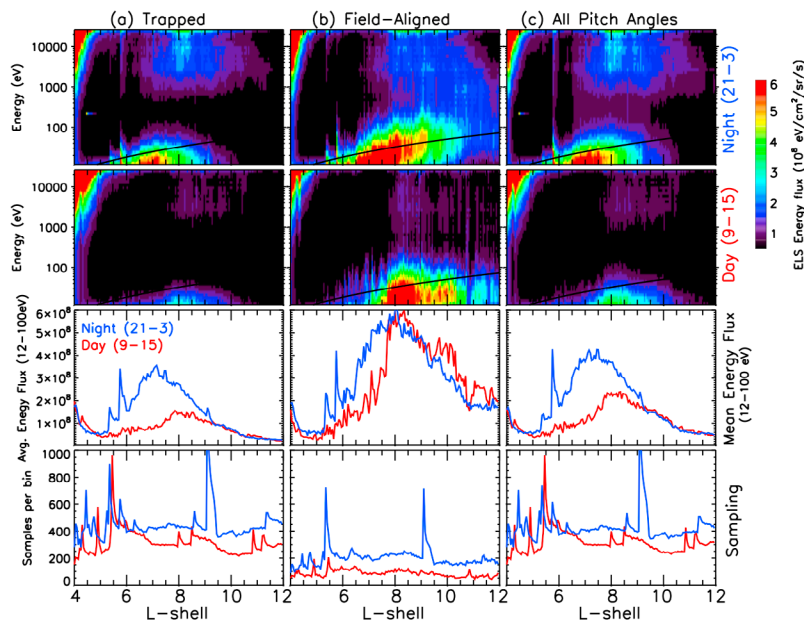[2]Mullard Space Science Laboratory, University College London, Dorking, UK.

Figure 1. Energy (12 eV to 26040 eV) versus L-shell (4 to 12) spectrogram for average fluxes of electrons with (a) pitch angle between 70°–110°, trapped electrons (b) field-aligned electrons, pitch angles less than 20° and great than 160° (c) all electrons, regardless of pitch angle. (top) Averaged over the night side (21-3 UT), (middle top) averaged over the dayside (9–15 UT), (middle bottom) the average energy fluxes for electrons with energies between 12 and 100 eV from the spectrogram above, red = dayside, blue = nightside. (bottom) Plots of the number of samples per bin (20 bins per L-shell). All data plotted are from CAPS ELS from 194 2004 to 100 2010 when Cassini is at latitudes from +10° to −10°.

between ±10° latitude. The electrons are separated into field-aligned (0° to 20° and 160° to 180°) pitch angles, trapped (70° to 110°) pitch angles, and all pitch angles (an average of all 8 detectors on ELS). Next, the data sets are binned in 0.05 L-shell increments (20 bins per L-shell) and averaged. Figure 1 shows the binned spectrograms of this averaging for trapped, field-aligned, and all pitch angles for the nightside (21-3 LT) in the first row and the dayside (9–15 LT) in the second row. The dawn and dusk regions are not included due to lack of coverage by the Cassini spacecraft. The color bar to the right of the plot shows electron energy flux with black indicating that fluxes are less than 0.5×10^8 eV/cm^2/sr/s and red peaking out at 6.0×10^8 eV/cm^2/sr/s. The red peak in the upper left corner of each spectrogram are penetrating electrons from the radiation belts.

[7] Figures 1 (top) and 1 (middle top) show a clear separation between the high and low energy electron fluxes at approximately 100 eV on both the dayside and the nightside, supporting the collective findings by *Sittler et al.* [1983], *Young et al.* [2005], and *Rymer et al.* [2007]. The higher energy electrons (>100 eV) possess a larger energy flux on the nightside at all pitch angles. Since the electrons in this energy range are directly related to interchange injections [*Burch et al.*, 2005; *DeJong et al.*, 2010], it appears that, when averaging the equatorial CAPS ELS data from mid 2004 to early 2010, there is a preference for interchange injections to occur on the nightside.

[8] Figure 1 (middle bottom) is the average energy flux for 12–100 eV electrons for both the dayside (red) and the nightside (blue). By inspecting these line plots, along with the spectrograms in the top two rows, we find asymmetries

between the dayside and nightside of the inner magnetosphere of Saturn. Both the trapped electrons (Figure 1a) and all pitch angle electrons (Figure 1c) show a large difference in the average energy flux of 12–100 eV electrons between dayside and nightside. By contrast, both the dayside and nightside field-aligned electrons (Figure 1b) have approximately the same average energy flux.

[9] The day-night asymmetry in the penetration of the 12–100 eV electrons into the inner magnetosphere represents one of the key results from Figure 1. There is a sharp decrease in the average energy flux for these electrons just inside of L = 8 on the dayside. The decrease also corresponds with a reduction in the high energy (>100 eV) electron fluxes a L = 8. In contrast, on the nightside the high energy electrons penetrate into L~6.5, while the low energy electron fluxes slowly decrease in until L = 5. This asymmetry occurs in all three pitch angle categories, and can be seen in the line plots of 12–100 eV electrons (third row).

[10] Our results are similar to those of *Paranicas et al.* [2010] and *Carbary et al.* [2009], who both used LEMMS electron data. *Paranicas et al.* [2010] found that trapped electrons in the 41–60 keV range show the same asymmetry as our electron fluxes. Their dayside electrons had less energy flux and only penetrated in to L = 8, while their nightside electrons extended inward to L = 5.5. Similarly, *Carbary et al.* [2009] examined higher energy (110–365 keV) electrons and found penetration to L = 8 on the dayside and to L = 5 on the nightside. These findings along with ours, suggests an energy independent local-time asymmetry in Saturn's magnetosphere that does not allow the electrons to penetrate any deeper than L = 8 on the dayside. These penetration differences could also be explained by enhanced
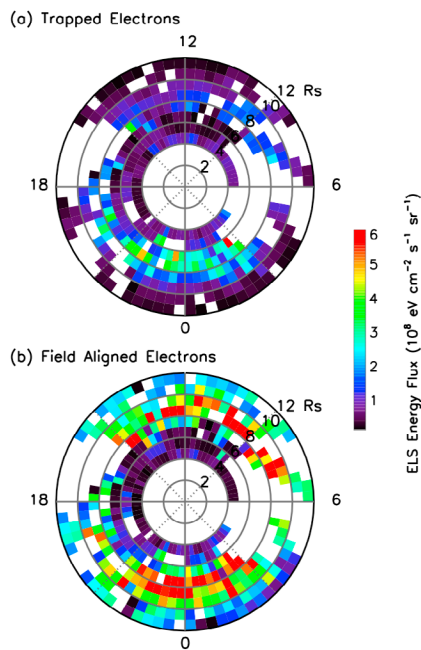
Figure 2. Local time plot of the average energy flux for 12–100 eV electrons (a) trapped electrons 70°–110° pitch angles and (b) field aligned pitch angles less than 20° and great than 160°. Both plots use the color scale on the right. This is the same data used in Figures 1a (top), 1a (middle top), 1b (top), and 1b (middle top).

plasma pressure on the dayside relative to the nightside magnetosphere [*Krimigis et al.*, 2007], where the lower pressures on the nightside allow stronger injections to move deeper into the magnetosphere.

[11] Figure 1 (bottom) shows the number of samples per bin (20 bins per 1 R_S) for the dayside (red) and nightside (blue). Note that there is higher sampling by CAPS ELS on the nightside than the dayside for all three pitch angle categories. Similarly, there are almost 3 times more trapped electrons than field-aligned electrons. However, since we are investigating the averages of each pitch angle population, the comparison between trapped and field-aligned electrons, and the comparison between the dayside and nightside electrons remains unbiased. On the other hand, when examining the average electron fluxes all pitch angles (Figure 1c), the trapped electrons dominate and cause the spectrograms and plots to appear more like the trapped electrons.

[12] Figure 2 is an alternative approach to visualizing the distribution of the average of the energy fluxes for 12–100 eV electrons. The energy fluxes for the 12–100 eV electrons have been averaged and binned by 1 hour of local time and 1 R_S. While, this method possesses less resolution than that of Figure 1, similar patterns can still be seen (note that white pixels indicates no data). The trapped electron fluxes once again exhibit a strong asymmetry, with the nightside having a higher average energy flux than the dayside. While there is also a similar asymmetry for the 12–100 eV field-aligned electrons, it is not as apparent. Both plots indicate a peak in average energy flux occurs at 8 R_S, as those of *DeJong et al.* [2010].

[13] The sampling for each bin in Figure 2 is shown in Figure 3 in order to ensure that the local time dependence is

not just an artifact of sampling. The correlation between the trapped plots (Figures 2a and 3a) and the field-aligned plots (Figures 2b and 3b) are 8.4% and 10.9% respectively. These results indicate that less than 11% of the local time dependence of the electrons can be accounted for by the sampling distribution.

3. Discussion and Conclusions

[14] *DeJong et al.* [2010] showed that electron energy fluxes between 12 to 100 eV inside of 12 R_S are related to interchange injections. In this study, we reveal a local time dependence of these electrons and therefore a day-night asymmetry in interchange injections. The energy flux for these cool electrons is intensified on the nightside for trapped electrons, while field-aligned electrons show very little local time variation in the amount of their average energy flux. Both trapped and field-aligned electron energy fluxes exhibit a sharp decrease at L = 8 on the dayside. The nightside electrons, on the other hand, slowly decline in average energy flux until L = 5. This suggests a mechanism in Saturn's magnetosphere that keeps injections from progressing inward of L = 8 on the dayside.

[15] Our results, combined with those of *Paranicas et al.* [2010] and *Carbary et al.* [2009], demonstrate that the local time differences in penetration of electrons into the inner magnetosphere of Saturn appears to be independent of energy. Thus, it seems unlikely that this penetration asymmetry is due solely to differences between the dayside and nightside absorption of the electron. If this were the case, we would expect larger differences in the L-shell penetration for different electron energies, characteristic of absorption by neutrals.

[16] One possible explanation for this asymmetry in the electron fluxes is reconnection events on the nightside as
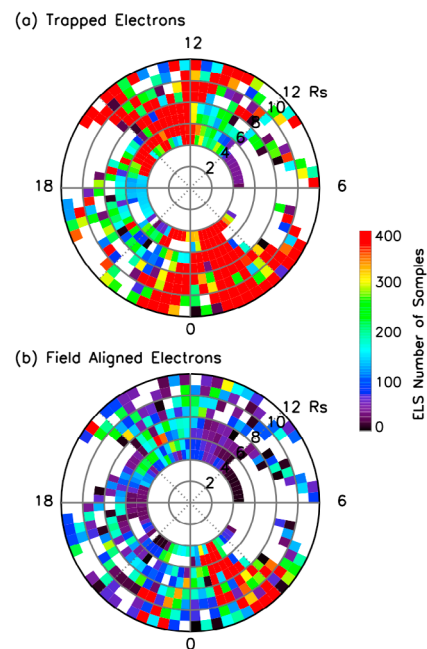
Figure 3. Local time plot of the number of samples in each bin for the plots in Figure 2. Both plots use the color scale on the right.

noted by *Mitchell et al.* [2005], *Jackman et al.* [2007], and *Hill et al.* [2008]. However, *McAndrews et al.* [2009] used CAPS data to investigate 35 depleted plasma regions in the tail and conclude that none of their events were created by tail reconnection. Their results indicate that reconnection events in the tail are difficult to measure using CAPS data. Also, from *DeJong et al.* [2010] and *Burch et al.* [2005], the electrons both above and below 100 eV as measured by ELS are related to injections; therefore it is more likely that these penetration differences are related to interchange and not reconnection.

[17] *Krimigis et al.* [2007] noted large differences in the plasma pressure between the dayside and nightside magnetosphere outside of 10 R_S. Higher pressure on the dayside translates to less pressure difference between the inner and outer magnetosphere in that region. This in turn results in less instabilities, resulting in weaker interchange injections on the dayside. The lower pressure outside of 10 R_S on the nightside will increase the strength of the instabilities giving the injections more momentum and allowing them to penetrate deeper into the magnetosphere. While these pressure differences may partial account for local time asymmetries in penetration of the electrons into the inner magnetosphere other mechanisms must be taken into account. If these asymmetries were solely due to pressured differences we should still see electrons inside of 8 R_S on the dayside since the nightside injections would rotate to the dayside in approximately 5 hours.

[18] *Chen and Hill* [2008] found an asymmetry of injection events to favor the pre-noon quadrant, however they excluded young or local injections in their study. Additionally, by tracing injections back to their point of origin, *Müller et al.* [2010] found hot plasma injections occur primarily in the night and morning sectors between 21 and 9 LT. Furthermore, *Mitchell et al.* [2005] state that ion acceleration events take place predominately on the night side. Thus, the local time asymmetries that we identify in the CAPS ELS 12–100 eV electron flux data further supports those of *Müller et al.* [2010] and *Mitchell et al.* [2005]. However, our analysis only evaluates the mean electron energy flux and does not address the individual injections. Therefore, the next step in understanding the relationship between 12–100 eV electrons and injections is to quantify the correlation between the amount of energy flux and the age of the injections. From our current studies, we anticipate that younger injections will correlate with 12–100 eV electron energy flux.

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